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13. ABSTRACT (Maximum 200 words) The research project is developing simulation methods so that it is possible to design and analyze advanced theater missile defense interceptors. We are focussing on the effects of body geometry on the stability of the boundary layer, in an attempt to delay transition to turbulence on these interceptors. We have used a recently developed computational fluid dynamics method to produce very accurate mean flow fields. We have parallelized a linear stability theory code and have applied it to a number of relevant geometries and flows. We find that increased free-stream enthalpy tends to stabilize the boundary layer and that nose bluntness has a very stabilizing effect. Both of these observations have been made in previous experiments. We plan to continue the analysis of these flows to better understand how to control and delay transition in hypersonic boundary layers.				
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SIMULATION OF TMD FLOWFIELDS

FINAL PROGRESS REPORT

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U.S. ARMY RESEARCH OFFICE

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STATEMENT OF THE PROBLEM STUDIED

The research project developed simulation methods for the design and analysis of advanced theater missile defense interceptors. We concentrated on studying the effects of body geometry and flow field chemistry on the stability of the boundary layer, in an attempt to delay transition to turbulence on these interceptors. A recently-developed computational fluid dynamics method was used to produce very accurate mean flow fields. We then developed a parallelized linear stability theory code and applied it to a number of relevant geometries and flows. We found that increased free-stream enthalpy tends to stabilize the boundary layer and that nose bluntness has a very stabilizing effect. Both of these observations have been made in previous experiments, and our new results further quantify this effect. To generalize these results, we have nearly finished the development and testing of a new parabolized stability equation (PSE) code, that includes complete finite-rate chemical reactions and non-linear interactions between disturbances. This code will allow a wider range of geometries and flow conditions to be studied, as well as simulation into the non-linear interaction regime to further understand the effects of chemistry on transition development. Our results suggest a number of means for the control and delay of transition in hypersonic boundary layers.

SUMMARY OF MOST IMPORTANT RESULTS

The research project consisted of two main topics. First, extensive method development took place so that interceptor seeker head geometries could be studied. Once these codes were complete and tested, they were used to study the effects of body geometry and flow field chemistry on transition to turbulence. In the following section, the key findings related to these two areas are discussed.

Linear Stability Theory and PSE Code Development

The research project involved the study of transition to turbulence under hypersonic flight conditions where finite-rate internal energy relaxation and chemical reactions take place. Prior to this research, there was no available computer code to perform these calculations. Therefore, the first part of the project involved the development of general-purpose transition prediction codes. Two types of codes were developed.

First, a linear stability theory code was developed that predicts how small disturbances are amplified as they pass through a hypersonic boundary layer. This formulation requires a flow that is essentially parallel to the body surface with little flow curvature. It also does not allow non-linear interaction between the different disturbance frequencies. It relies on a highly accurate mean flow solution for the flow field of interest. To obtain these flow

fields, we used a previously-developed efficient parallelized computational fluid dynamics method.

The results from the linear stability theory (LST) code were used to predict transition through the use of the e^N method. In order to compute the local frequency-dependent N factor, a numerical integration method was developed. This allowed the prediction of transition for a specified maximum N factor.

The second type of transition prediction code that was developed is based on the parabolized stability equations (PSE). In this case, the important non-linear terms are included in the stability calculations. Also, the effects of non-parallel flow and flow curvature are included in the analysis. This allows more general flows to be simulated and the analysis of the transition process may be performed. This method has been developed and tested, except for the inclusion of the non-linear interaction terms. The final aspect of this work will be completed in the next several months, at which time the code will be available for release.

These codes represent unique tools for the analysis of transition of hypersonic flows. The effects of flow field chemistry are included so that accurate results may be obtained. Dr. Michael Holden of the Calspan - University of Buffalo Research Center has requested that we use the LST and PSE codes to simulate a series of his recent TMD interceptor seeker head experiments. This work will help verify the transition simulation methods and will clarify why some seeker head geometries are more prone to transition than others.

Results of Transition Studies

The primary emphasis of the research project was on the analysis of the effects of flow field chemistry and geometry on transition to turbulence in hypersonic flows. There are two types of calculations that we performed: sharp cone flows to reproduce experimental data, and more realistic blunted geometries.

Hornung and co-authors performed a series of experiments on sharp cones in the California Institute of Technology Free-Piston Shock Tunnel T5. They used heat transfer gauges to determine the location of transition for different gases as a function of enthalpy. These experiments showed that the transition Reynolds number increases with increasing free-stream total enthalpy.^{1,2} Figure 1 plots the transition Reynolds number for 5° sharp cones as a function of total enthalpy for nitrogen, air, and carbon dioxide flows. We see that the increase in the transition Reynolds number is greater for carbon dioxide than for air, which is greater than for nitrogen. This is postulated to be a result of increased endothermic reactions and internal energy excitation, because the increase in

transition Reynolds number corresponds to the ease with which the gas absorbs energy. These reactions and internal energy relaxation are assumed to absorb energy from the instability waves.

Previous experimental investigations of transition were limited to cold flows where high Mach numbers were primarily achieved by lowering the speed of sound, and the kinetic energy was not large enough to cause molecular dissociation effects to become important.

We have used the linear stability theory codes developed under this research project to study the sharp cone flows. Figures 2 and 3 show that with the e^N method with the N factor equal to 6 (typical of non-quiet wind-tunnel experiments), both the linear stability theory (LST) and parabolized stability equations (PSE) calculations predict the experimental data very well. Most importantly, the trends are reproduced and we see that the enthalpy effect is predicted by the theory. This indicates that hypersonic flows may be stabilized by naturally-occurring chemical reactions. This would imply that at actual flight conditions, hypersonic flows are more stable than had been previously realized. Also, it should be noted that under actual flight conditions, the N factor for transition should be closer to $N = 10$, indicating a further increase in transition Reynolds number.

In an attempt to understand how the chemical reactions affect the amplification of disturbances, many parametric studies were undertaken. For example, Fig. 4 shows a case where the chemical reactions have been artificially modified in the LST portion of the calculation. In one case, the sign of the heat of formation has been reversed, making the reactions effectively exothermic; in another case the reactions are disabled. We see that the realistic endothermic (heat absorbing reactions) have the smallest amplification rate, $-\alpha_i$. The exothermic reactions have dramatically increased amplification rates, while the non-reacting case lies in between. This further illustrates that endothermic reactions tend to stabilize hypersonic flows by absorbing fluctuation energy.

We have also made extensive studies to see if the boundary layer is tuned to a certain reaction or internal energy relaxation mode. This would make sense because the second mode is most unstable in these flows, resulting in a most unstable frequency closely tuned to the local speed of sound and boundary layer thickness. However, all of our attempts to isolate a specific rate process that is responsible for the stabilization effect were inconclusive. It appears that the stabilization by finite-rate processes is broadband and does not affect one frequency more than another. Further work on this issue is warranted.

The second set of calculations that we performed concerned transition to turbulence on a more realistic three-dimensional seeker head geometry. We chose a generic sphere-

triconic geometry with symmetric planar slices where a seeker window could be located. Figures 5 and 6 show front and side views of the interceptor seeker head geometry considered. Our linear stability calculations indicated that for this geometry under the typical flight conditions considered (20 km altitude and 4.0 km/s), the flow is stable and does not transition. We showed that this is a result of the nose bluntness by considering equivalent sharp cone geometries. We also considered the possibility of cross-flow transition using the transition criterion of Reed and Haynes.³ As shown in Fig. 7, near the back end of the seeker head the flow may be transitional. However, this is beyond the location of the windows.

In the equivalent-cone calculations, it was interesting to note that the flow field chemistry is destabilizing and leads to earlier transition than the non-reacting analysis. This is due to the fact that the chemical reactions alter the mean flow, making the boundary layer inherently more unstable. The stabilizing effect of the finite-rate chemistry on the disturbance amplification was not weaker than this mean flow effect, resulting in earlier transition. Therefore, the design and analysis of interceptor seeker heads must be done carefully. The methods developed under this project make this type of design possible.

Further details of the method development and analysis of hypersonic transition may be found in our publications that are listed below.

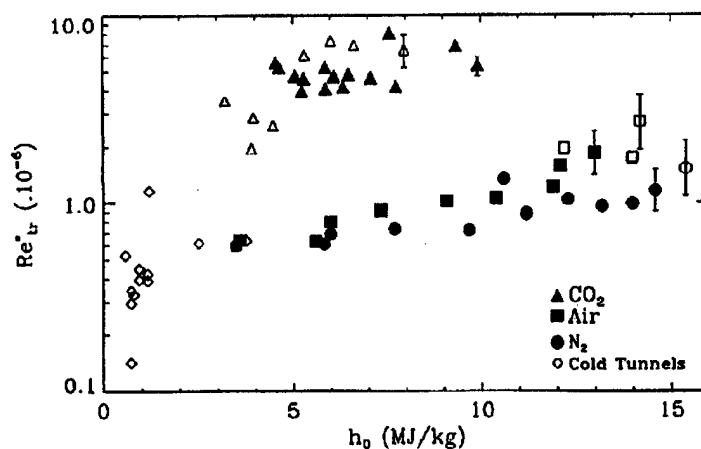


Figure 1. Transition Reynolds number (based on reference conditions) as a function of free-stream total enthalpy measured in the Caltech T5 Shock Tunnel. Taken from Ref. 1.

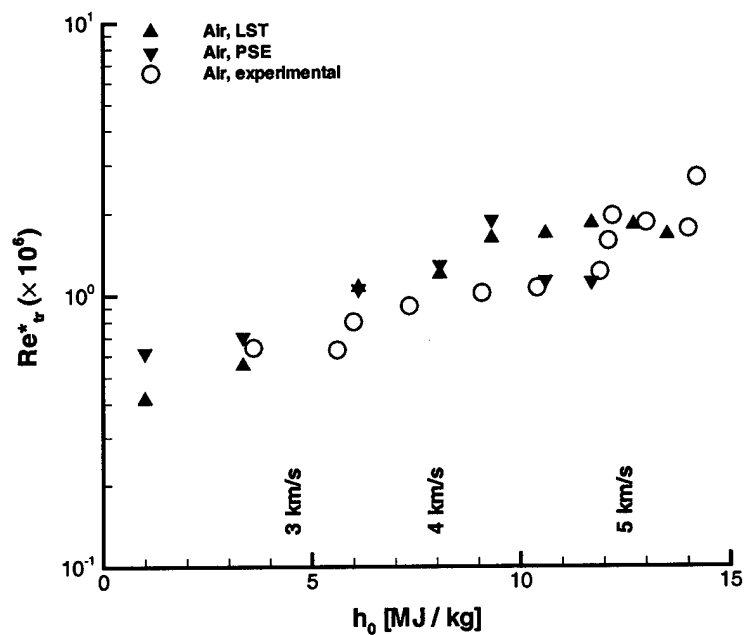


Figure 2. Transition Reynolds number, Re_{tr}^* , vs. freestream total enthalpy for air. Experimental data from Germain and Hornung (1997), and Adam and Hornung (1997).

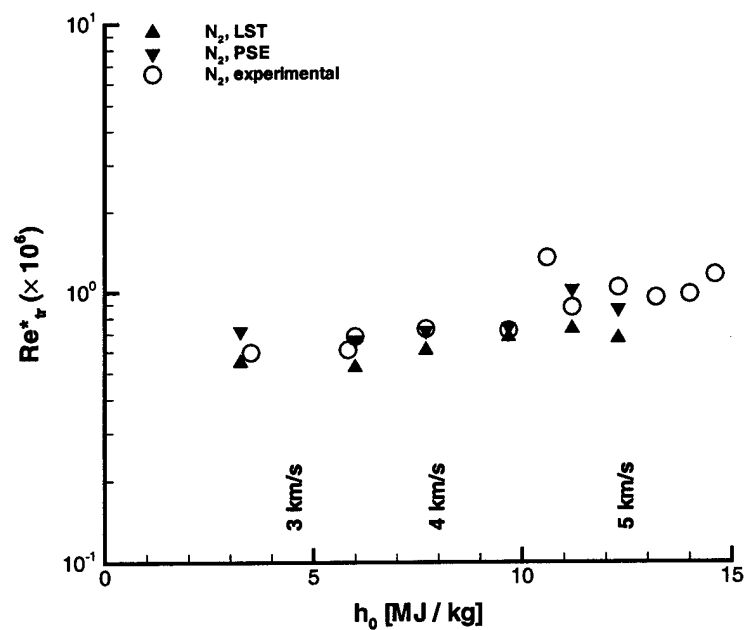


Figure 3. Transition Reynolds number, Re_{tr}^* , vs. freestream total enthalpy for nitrogen. Experimental data from Germain and Hornung (1997), and Adam and Hornung (1997).

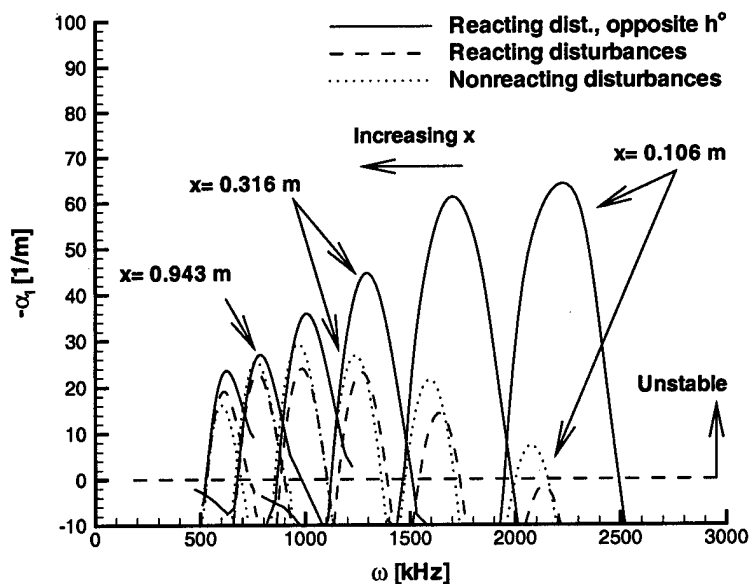


Figure 4. Amplification rates for disturbances with reaction in a mean flow of air calculated with reaction, and where the heats of formation have been reversed in the disturbances. Also shown are the cases with the correct heats of formation for disturbances with and without reaction, Shot 1162.

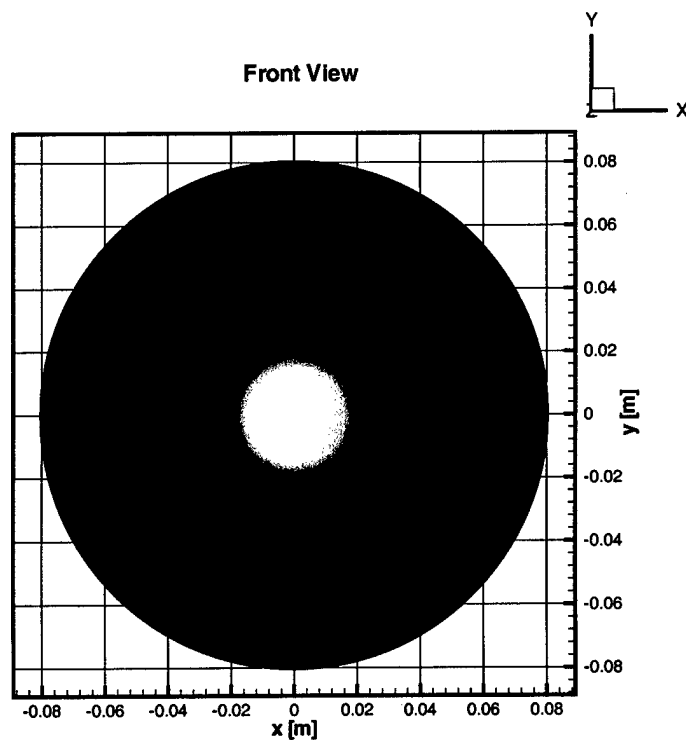


Figure 5. TMD interceptor geometry used in these calculations. Front view.

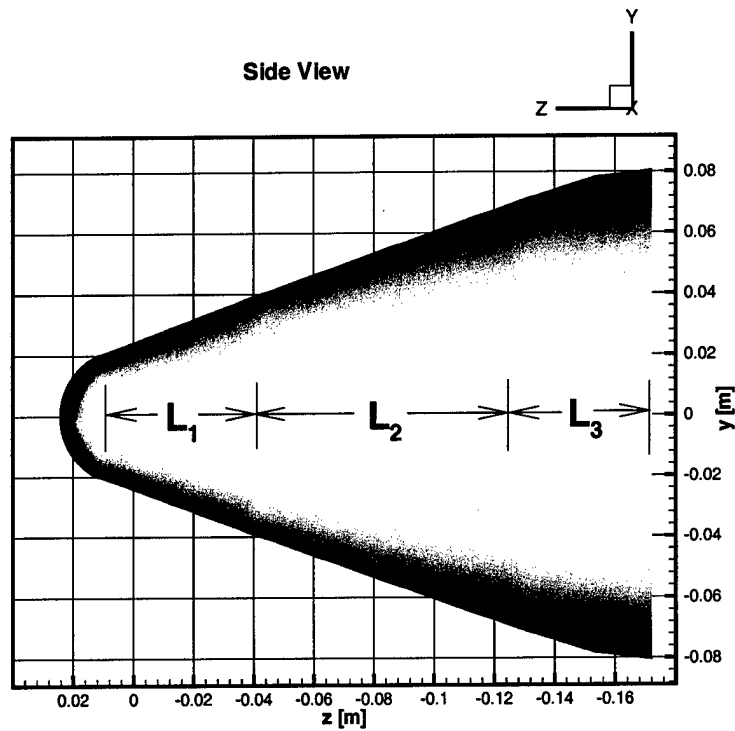


Figure 6. TMD interceptor geometry used in these calculations. Side view.

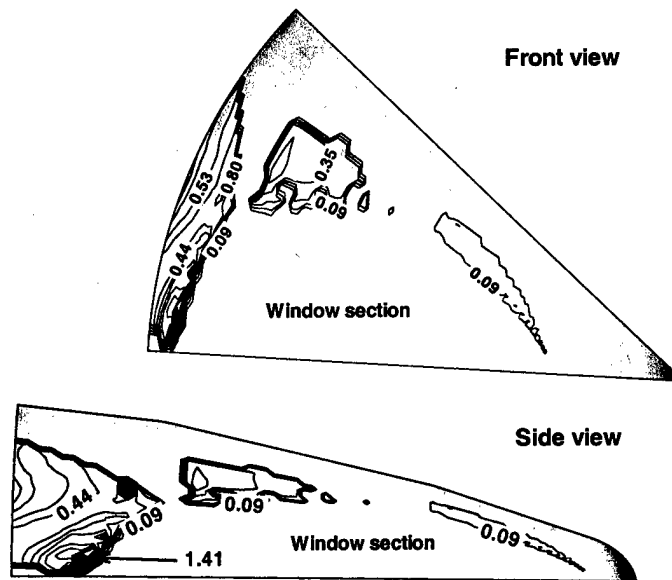


Figure 7. Contour lines showing the ratio of crossflow Reynolds number to crossflow transition Reynolds number, in regions where $2\% < W_{max}/U_e < 8\%$

LIST OF PUBLICATIONS

1. H.B. Johnson, G.V. Candler, and M.L. Hudson, "Numerical Study of Hypersonic Boundary Layer Transition on a Blunt Body," *AIAA Paper No. 97-0554*, Jan. 1997.
2. H.B. Johnson, T.G. Seipp, and G.V. Candler, "Numerical Study of Hypersonic Reacting Boundary Layer Transition on Cones," *AIAA Paper No. 97-2567*, June 1997.
3. H.B. Johnson, and G.V. Candler, "Thermochemical Interactions in the Linear Stability of Hypersonic Boundary Layers," *AIAA Paper No. 98-2438*, June 1998.
4. H.B. Johnson, T.G. Seipp, and G.V. Candler, "Numerical Study of Hypersonic Reacting Boundary Layer Transition on Cones," *Physics of Fluids*, Vol. 10, No. 10, pp. 2676-2685, Oct. 1998.
5. H.B. Johnson, and G.V. Candler, "PSE Analysis of Reacting Turbulent Boundary Layer Transition," *AIAA Paper No. 99-3793*, July 1999.

PERSONNEL SUPPORTED

1. Graham V. Candler, Principal Investigator.
2. Heath B. Johnson, Master's of Science in Aerospace Engineering, University of Minnesota, December 1997; Ph. D. in Aerospace Engineering, University of Minnesota, anticipated June 2000.
3. Trevor G. Seipp, Master's of Science in Aerospace Engineering, University of Minnesota, January 1997.
4. Krishnendu Sinha, Master's of Science in Aerospace Engineering, University of Minnesota, June 1998.

REPORT OF INVENTIONS

None.

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2. P.D. Germain and H.G. Hornung, "Transition on a Slender Cone in Hypervelocity Flow," *Experiments in Fluids*, Vol. 22, No. 3, pp. 183-190, Mar. 1997.

3. H.L. Reed and T.S. Haynes, "Transition Correlations in Three-Dimensional Boundary Layer," *AIAA Journal*, Vol. 32, No. 5, pp. 923-929, May 1994.